Task 3 Report – Field Batching/Mixing

Project Title: Feasibility of Non-Proprietary Ultra-High Performance Concrete (UHPC) for use in Highway Bridges in Montana: Phase II Field Application

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1 Introduction

Ultra-high performance concrete (UHPC) has mechanical and durability properties that far exceed those of conventional concrete. However, using UHPC in conventional concrete applications has been cost prohibitive, with commercially available/proprietary mixes costing approximately 30 times more than conventional concrete. Previous research conducted at Montana State University (MSU) resulted in non-proprietary UHPC mixes made with materials readily available in Montana (Berry, Snidarich, & Wood, 2017). These mixes are significantly less expensive than commercially available UHPC mixes, thus opening the door for their use in construction projects in the state. The MDT Bridge Bureau is interested in using UHPC in field-cast joints between precast concrete deck panels. The use of UHPC in this application will reduce development lengths, and subsequently reduce the requisite spacing between the decks and improve the overall performance of the bridge. A second phase of research is being conducted at MSU that will build on the non-proprietary UHPC research already completed, and focus on ensuring the successful application of this material in these field-cast joints. Specifically, this research will investigate several items related to the field batching of these mixes, and the potential variability in performance related to differences in constituent materials. Further, rebar bond strength and the subsequent effect this has on development length will be investigated.

The specific tasks associated with this research are as follows.

Task 1 – Literature Review

Task 2 – Material Sensitivity

Task 3 – Field Batching/Mixing

Task 4 – Bond/Development Length Characterization

Task 5 – Analysis of Results and Reporting

This report documents the work completed as part of Task 3 – Field Batching/Mixing. It should be noted, that this task will continue to be updated as new results becomes available.

2 Methods

This chapter discusses the methods used to prepare and evaluate the UHPC mixes in this research.

2.1 Mixing Procedure

The small laboratory mixtures were produced in an industrial benchtop Hobart A200 mixer in 0.20-ft^3 batches (Figure 1). The A200 is a ½-horsepower mixer with a 20-quart capacity bowl. The larger-scale mixes were produced in an IMER Mortarman 360 high-shear horizontal mortar mixer (Figure 2). The IMER Mortarman was powered by an 11-hp gas engine, and has a drum capacity of 12 ft^3. However, it should be noted that this mixer cannot yield 12 ft^3 of UHPC due to the nature of the mixing procedure and the state of the materials prior to the UHPC becoming fluid.

The mix procedure used in this research is summarized below. Note that this procedure is similar to that proposed by Wille and Naaman (2011) and FHWA (2013).

- Combine fine aggregate and silica fume. Mix for 5 minutes on low speed.
- Add cement and fly ash to mixer. Mix for 5 minutes on low speed.

- Combine water and HRWR in separate container. Mix thoroughly.
- Add water & HRWR to mixing bowl. Mix on low speed until mix becomes fluid (typically around 5-6 minutes).
- Add steel fibers and mix for approximately 3 minutes after becoming fluid.

It should be noted, that mixing UHPC for more than 10 minutes after it first becomes fluid was shown to have detrimental effects on concrete strength. It is suspected that this effect may be due to an increase in entrapped air within the mix. This will be investigated further as this research progresses.

Figure 1: Hobart A200 Mixer

Figure 2: IMER Mortarman 360 mixer

2.2 Flow Testing Procedure

Workability was measured via a spread cone mold in accordance with ASTM C1856 -- Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete (ASTM, 2017). Prior to removing any UHPC from the batching container, a wetted spread cone was placed on a flow table and a single scoop of UHPC was used to fill the spread cone. The spread cone was then lifted from the base, and the remaining material in the cone was scraped off onto the base plate. A maximum and minimum diameter was recorded after two minutes, and the batch spread was recorded as the average of these two diameters. The spread cone and a typical UHPC spread are shown in Figure 3.

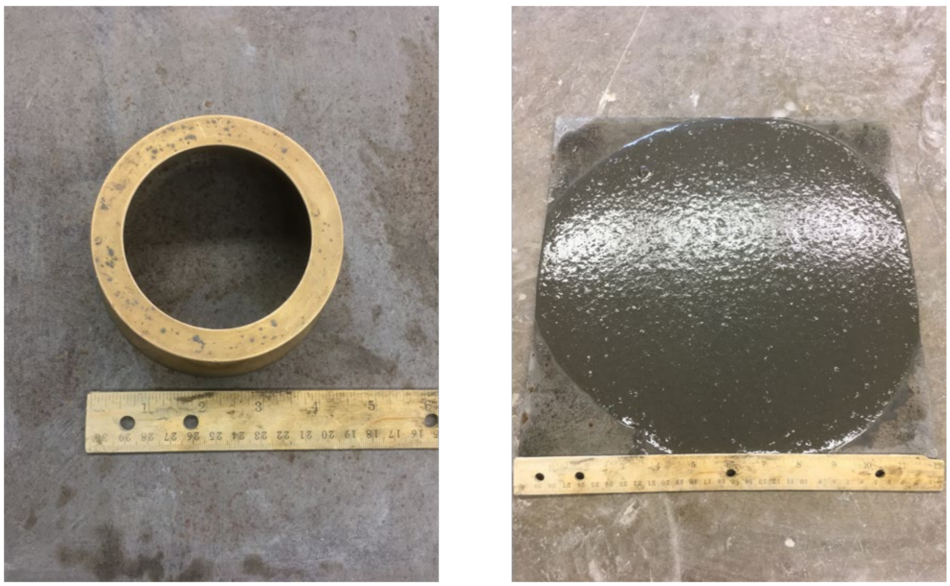


Figure 3: Spread Cone Mold & Measurement of Flows

2.3 Specimen Casting, Preparation, and Curing

For each batch, 3-by-6-in test cylinders were prepared in substantial accordance ASTM C1856 -- Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete (ASTM, 2017). The UHPC was placed into reusable plastic cylinder molds in a single lift, and were consolidated by tapping on the sides with a mallet. Rather than using the plastic caps that accompanied cylinder molds, a single layer of plastic wrap was placed over the cylinders and tightly secured to prevent any surface drying at the specimen surfaces.

After approximately 48 hours, cylinders were removed from the molds, and a diamond-blade tile saw was used to remove the uneven top surface of the cylinder. The cylinders were then ground using an automatic cylinder end grinder (Figure 4), and placed in a temperature-controlled cure room at 100% humidity until the respective test date.

Figure 4: Cylinder end grinder and prepared specimen

2.4 Compression Testing

The compressive strength of the concrete was determined in substantial accordance to ASTM C 1856 -- Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete-- by testing at least three 3-by-6-in cylinders loaded to failure in a Testmark CM Series hydraulic compression load frame with a 400,000-pound capacity. The cylinders were loaded at a target rate of 975-1075 lbs/second (138-152 psi/s). The maximum load at failure was recorded and used to determine the maximum average compressive strength of the UHPC mix at the specified testing intervals.

Figure 5: Compression cylinder in load frame

2.5 Flexural Testing

The flexural tensile strength of the concrete was calculated as the average of two 20-by-6-by-6 inch prisms tested according to ASTM C78 -- Standard Test Method for Flexural Strength of Concrete (ASTM, 2018). A typical flexural specimen in the load frame is shown in Figure 6. It should be noted that the steel fibers included in the UHPC mix allow the flexural specimens to continue to carry load beyond the formation of an initial crack; therefore, the measured ultimate load from these tests do not provide a good measure for the initial cracking capacity of the concrete. In this research, the initial cracking was determined from the recorded force-deformation response of each specimen by finding the first point at which there is a sudden reduction in applied load and a distinct reduction in stiffness. It should be noted that this point was clearly defined for the specimens in this research.

Figure 6: Flexural test specimen in load frame

2.6 Set Time Estimation

The set times of the UHPC were determined in substantial accordance to ASTM C403 -- Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance (ASTM, 2016). Set time was determined by applying the penetrometer needle at a constant pressure on the specimen surface over the course of 10 seconds until the circumscribed marker reached the specimen surface. The penetration resistance was determined via reading the pressure in pounds per second from the base of the friction ring. The accompanying time elapsed since water addition was recorded in conjunction with each penetration resistance measurement. A minimum of two penetrometer readings were taken per time interval, and penetration measurements were averaged. Penetration measurements were taken approximately every 30 minutes until the capacity of the pocket penetrometer was reached. At least four penetration measurements were taken per specimen. Penetration resistance was plotted with accompanying elapsed time. Data points were used to fit a logarithmic regression curve to measured data in order to estimate initial and final set times.

3 Materials

This section discusses the materials used in this research.

3.1 Portland Cement

Two cement sources were used in this research to investigate the effects of varying cement source: Trident and Ash Grove. The Trident cement was a Type I/II/IV cement from the GCC cement plant in Trident, MT, and was used in original mix development (Berry et al., 2017). The Ash Grove cement was a Type I/II cement from the Ash Grove cement plant in Clancy, MT. Chemical and physical properties of the cement are included in Table 1, along with the applicable C150 limits.

Table 1: Chemical and Physical Properties of Portland Cements

Chemical Properties	**C150 Limit**	**Trident**	**Ash Grove**
SiO_2 (%)	NA	20.8	20.8
Al_2O_3 (%)	6.0 max	4.0	3.9
Fe_2O_3 (%)	6.0 max	3.2	3.3
CaO (%)	NA	64.7	63.9
MgO (%)	6.0 max	2.2	3.7
SO_3 (%)	3.0 max	2.8	2.1
Loss on Ignition (%)	3.0 max	2.7	2.1
Insoluble Residue (%)	0.75 max	0.3	0.9
CO_2 (%)	NA	1.6	1.6
Limestone (%)	5.0 max	3.6	4.2
$CaCO_3$ in Limestone (%)	70 min	98.0	86.8
Inorganic Processing Addition (%)	5.0 max	0.5	-
Potential Phase Compositions:			
C_3S (%)	NA	57.0	59.0
C_2S (%)	NA	16.0	13.0
C_3A (%)	8.0 max	5.0	4.0
C_4AF (%)	NA	10.0	10.0
$C_3S + 4.75C_3A$ (%)	NA	-	78.0
Physical Properties			
Air Content (%)	12.0 max	7	8
Blaine Fineness (m2/kg)	260 min	418	414.2
Autoclave Expansion	0.80 max	0.006	
Compressive Strength (psi):			
3 days	1740	4240	3224
7 days	2760	5320	5239
Initial Vicat (minutes)	45 - 375	142	152
Mortar Bar Expansion (%) (C 1038)	NA	-0.008	-

3.2 Silica Fume

The silica fume used in this research was MasterLife SF 100 from BASF. The Chemical and physical properties of the silica fume are compared with the applicable ASTM C1240 limits in Table 2.

Table 2: Chemical and Physical Properties of Silica Fume, ASTM C1240

Item	Limit	Result
Chemical Properties		
SiO_2 (%)	85.0 min	92.19
SO_3 (%)	NA	0.31
CL^- (%)	NA	0.13
Total Alkali (%)	NA	0.85
Moisture Content (%)	3.0 max	0.45
Loss on Ignition (%)	6.0 max	3.07
pH	NA	7.94
Physical Properties		
Fineness (% retained on #325)	10.0 max	0.90
Density (specific gravity)	NA	2.26
Bulk Density (kg/m^3)	NA	739.32
Specific Surface Area (m^2/g)	15.0 min	22.42
Accelerated Pozzolanic Activity - w/ Portland Cement (%)	105 Min	140.41

3.3 Fly Ash

Three Class F fly ash sources were used in this research: Coal Creek, Genesee, and Sheerness. The Coal Creek ash was the sole fly ash studied in the original mix development, and was from the Coal Creek power plant in Underwood, North Dakota. The Genesee fly ash was from the Genesee Generating Station near Warburg, Alberta, and was supplied by the GCC cement plant near Trident, MT. It should be noted that the Genesee ash was used in this phase of research for almost all of the mixes, because this ash was the most readily available in the state at the time of this research. The Sheerness fly ash was supplied by the Ash Grove cement plant and obtained from the Sheerness Generating Station in Hanna, Alberta. The chemical and physical properties of the fly ashes are provided in Table 3, along with the ASTM C618 limits.

Table 3: Chemical and Physical Properties of Fly Ash Studied, ASTM C618

		Source		
Chemical Properties	**C168 Limit**	**Coal Creek**	**Genesee**	**Sheerness**
SiO_2 (%)	NA	55.0	59.9	52.3
Al_2O_3 (%)	NA	16.8	21.4	22.6
Fe_2O_3 (%)	NA	6.0	4.2	6.4
Sum of Constituents	70.0 min	77.8	85.5	81.2
SO_3 (%)	5.0 max	0.50	0.19	0.46
CaO (%)	NA	11.4	6.7	11.2
Moisture (%)	3.0 max	0.03	0.03	0.07
Loss on Ignition (%)	6.0 max	0.1	0.8	0.5
Available Alkalis, as Na_2O (%)	NA	0.9	-	-
Physical Properties				
Fineness (% retained on #325)	34% max	29.8	29.2	26.6
Strength Activity Index (% of control)				
7 days	75% min	78.0	89.6	83.3
28 days	75% min	93.0	84.3	88.2
Water Requirement (% control)	105 % max	95.0	95.3	95.8
Autoclave Soundness (%)	0.8% max	-	0.07	0.06
True Particle Density (g/cm^2)	NA	2.42	-	2.25

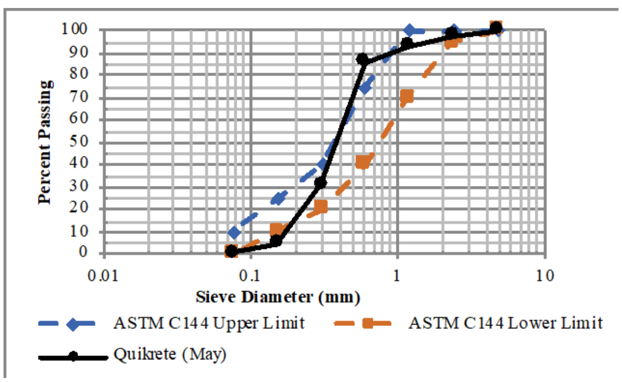
3.4 Aggregates

During the initial phase of research (Berry et al., 2017), masonry sand processed and packaged by QUIKRETE near Billings, MT, was used as the sole aggregate in the UHPC mixes. This sand was chosen due to its fineness, favorable gradation, economy, and availability, all of which are key to the development of a cost-effective UHPC mix design for use in Montana. To investigate the effects of varying sand source, the phase of research discussed herein investigated several other sand sources from across Montana. While the original research focused on only using a fine aggregate source that met the specifications for masonry sand (ASTM C144 - Standard Specifications for Aggregate for Masonry Mortar), this research also looked at using conventional concrete fine aggregates (ASTM C33 - Standard Specification for Concrete Aggregates). Conventional concrete fine aggregates were investigated because, in comparison to masonry sands, concrete sands are less expensive and more widely available from gravel pits across the state.

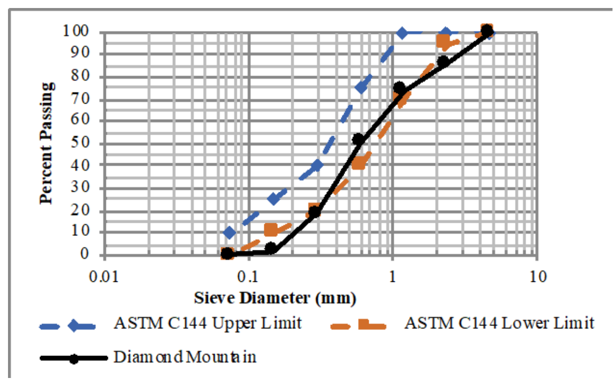
A variety of local fine aggregate sources were identified using the MDT Gravel Pit Index and obtained for use in this study. Specifically, five mason sands, four concrete sands, and two silica sands were examined during the aggregate variability study. The aggregate sources, locations, and key physical properties are provided in Table 4, while the gradation curves for each aggregate are provided in Figure 7 and Figure 8. Included in the gradation curves are the respective upper and lower ASTM limits for the particular aggregate type.

Table 4: Fine Aggregate Sources and Properties

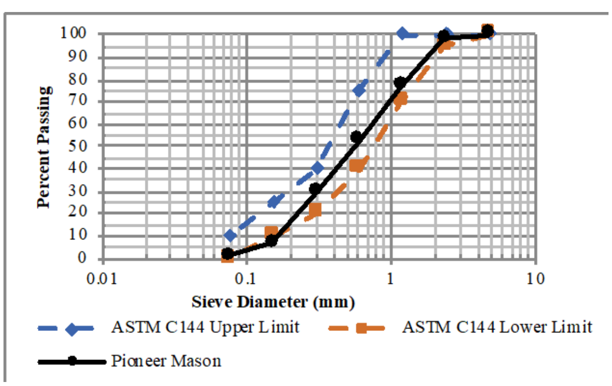
Fine Aggregate Source	Supplier	Location	FM	Absorption	OD S.G.	SSD S.G.
QUIKRETE	QUIKRETE	Billings, MT	3.32	1.87%	2.56	2.60
Diamond Mountain-Masonry	Diamond Mountain	Frenchtown, MT	4.68	3.99%	2.45	2.60
Pioneer-Masonry	Pioneer Concrete & Fuel	Butte, MT	4.35	1.90%	2.55	2.60
S&N-Masonry	S&N Concrete & Materials	Anaconda, MT	4.50	2.46%	2.50	2.56
Helena-Masonry	Helena Sand & Gravel	Helena, MT	4.12	2.24%	2.48	2.54
Capital-Masonry	Capital Concrete	East Helena, MT	4.22	2.41%	2.54	2.60
BBB&T-Concrete	BBB&T	Bozeman, MT	4.75	1.97%	2.61	2.66
Pioneer-Concrete	Pioneer Concrete & Fuel	Butte, MT	4.75	2.09%	2.50	2.55
S&N-Concrete	S&N Concrete & Materials	Anaconda, MT	5.07	2.68%	2.48	2.55
Helena-Concrete	Helena Sand & Gravel	Helena, MT	5.30	1.67%	2.49	2.54



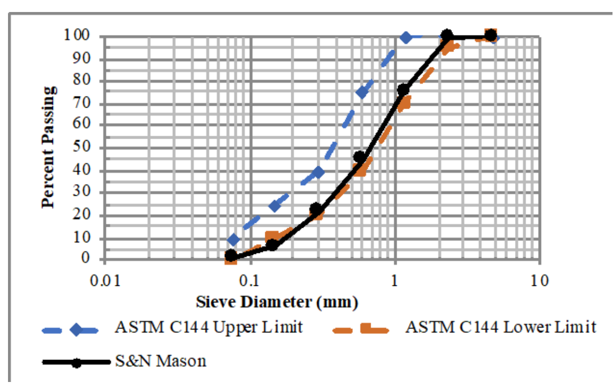
(a) QUIKRETE-Masonry



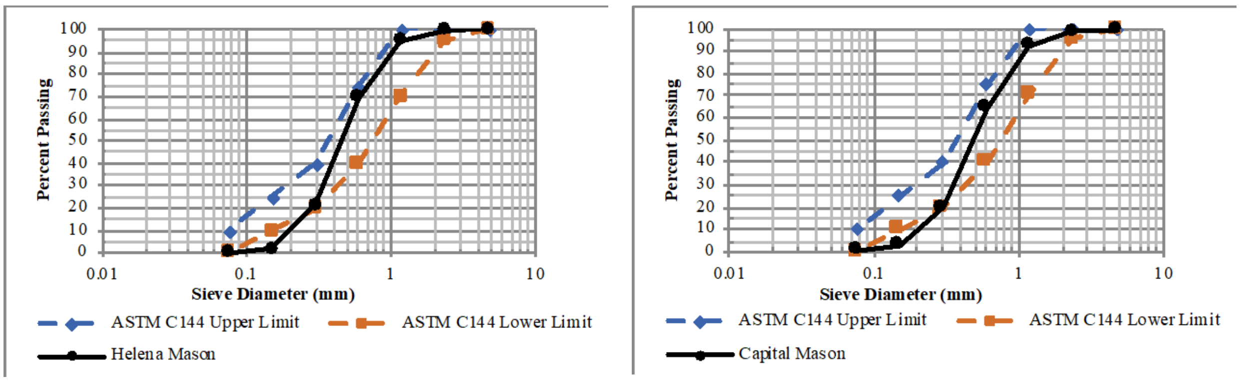
(b) Diamond Mountain-Masonry



(c) Pioneer-Masonry



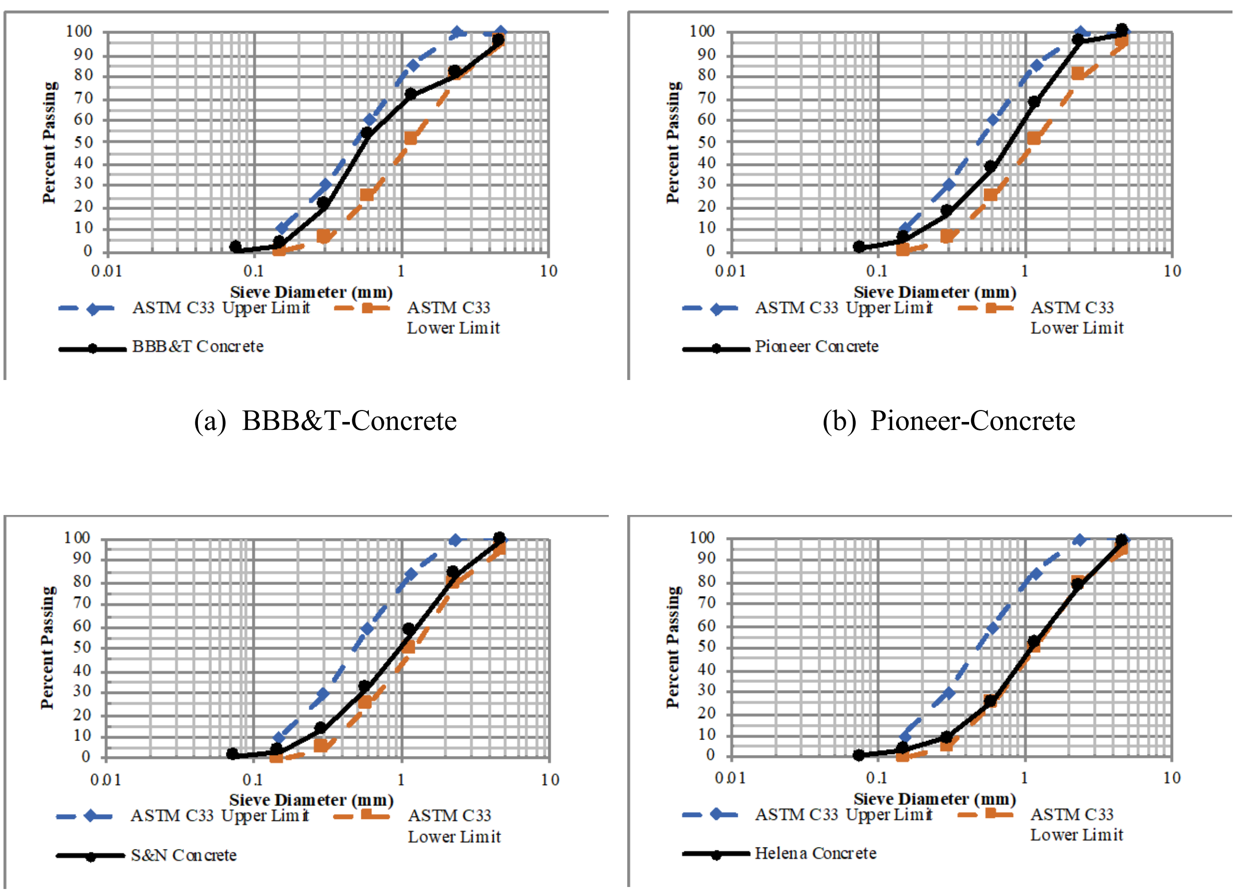
(d) S&N-Masonry



(e) Helena-Masonry

(f) Capital-Masonry

Figure 7: Particle Size Distribution of Mason Sands



(a) BBB&T-Concrete

(b) Pioneer-Concrete

(c) S&N-Concrete

(d) Helena-Concrete

Figure 8: Particle Size Distribution of Concrete Sands

3.5 High Range Water Reducer (HRWR)

This research used the same water reducer that was used in the original phase of research: CHRYSO Fluid Premia 150, which is a polycarboxylate ether (PCE)-based product. This HRWR was used because it was shown to provide the best workability and least amount of entrapped air.

3.6 Steel Fibers

The steel fibers used in the original mix development effort were 0.2 mm diameter by 13 mm in length, and were supplied by Nycon (Nycon-SF Type I "Needles"). However, the steel used in these fibers is not produced domestically, and therefore they are not permitted on federally-funded projects. The research discussed herein investigated using a domestically-produced fiber; specifically, the Bekaert Dramix OL 13/0.20. Properties of the two fibers are provided in Table 5. It should be noted that the Dramix OL 13/0.20 fibers have been proven to be a very effective fiber for use in UHPC, and are used extensively in UHPC applications nationally as they are the only domestically-produced drawn fiber of these dimensions and strength that are currently available on the market. However, at the time of writing, Bekaert has discontinued the domestic production of these fibers.

Table 5: Properties of Steel Fibers

Properties	Nycon-SF Type I	Bekaert Dramix OL 13/0.20
Length (mm)	13	13.0
Diameter (mm)	0.2	0.2
Aspect Ratio	65	65.0
Tensile Strength (ksi)	285	399.0
Elastic Modulus (ksi)	29000	29000
Coating	Copper	Copper

4 Sensitivity of UHPC to Mixing Variability and Field Conditions

4.1 Base Mix Design

The mix design recommended from the Phase I research effort (Berry et al., 2017) was used in this phase of research, with slight modifications. This mix was proportioned using the absolute volume method using prescribed values for water to cement ratio (w/c), high range water reducer to cement ratio (HRWR/c), supplemental cementitious materials to cement ratio (SCM/c -- includes silica fume and fly ash), silica fume to fly ash ratio (SF/FA), and sand to cement ratio (Sand/c). The base mix in this phase of research used cement from the Trident cement plant, fly ash from the Genesee Generating Station, concrete sand from Bozeman Brick and Tile, and Bekaert steel fibers.

The mix proportions for a 2.5 cu. ft mix are provided in Table 6. It should be noted that this mix design is identical to that used in the material sensitivity study discussed previously, with one exception – the amount of water. A majority of the mixes in this phase of research were at least 2.5 cu. ft and were mixed with the IMER Mortarman 360 mortar mixer, in contrast to the mixes in the material sensitivity study which were 0.2 cu. ft and were mixed using the industrial cake mixer. Early on, during initial trial batches using the larger batches, it was determined that the larger mixes required more water and HRWR, and therefore the mixes used in this phase of research included 10% more water and 10% more HRWR than the mixes used in the material sensitivity study. This increase in water was required to obtain the correct mix consistency and flow, and did not have a detrimental effect on strength.

Table 6: Mix Proportions for 2.5 cu. ft. Mix

Item	Item Type	Amount (lbs)
Water	-	27.66
HRWR	CHRYSO Fluid Premia 150	5.96
Portland Cement	Type I/II Trident	120.32
Silica Fume	BASF MasterLife SF 100	25.78
Fly Ash	Trident Genesee	34.38
Fine Aggregate	O.D. BBB&T Concrete Sand	144.11
Steel Fibers	Bekaert Dramix OL 13/0.20	24.34

4.2 Strength Gain vs Time

The strength gain of the UHPC mix developed in this research was measured over a 6-month period. The batch size used in this study was 2.5 cu. ft, and two identical mixes were tested. The measured compressive strength (average of 3 cylinders) for each mix is presented for the first 7 days in Figure 9, and over a 6-month period in Figure 10. As can be observed, both mixes had high early strengths, exceeding 10 ksi in the first 24 hours, and exceeding 14 ksi in the first week. The mixes continued to gain strength over time (with a few fluctuations), ultimately reaching compressive strengths of 20.4 and 19.1 ksi at 182 days.

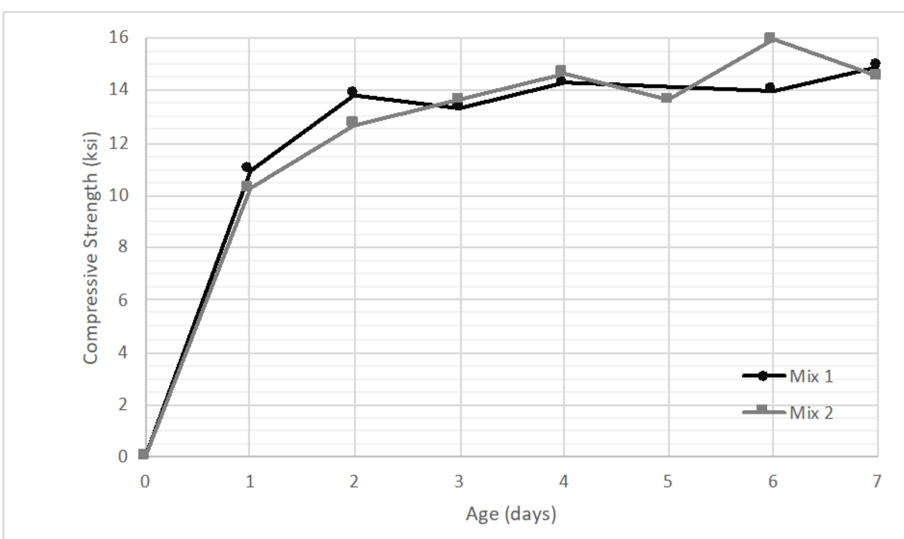


Figure 9: Strength Gain vs Time – 7 Days

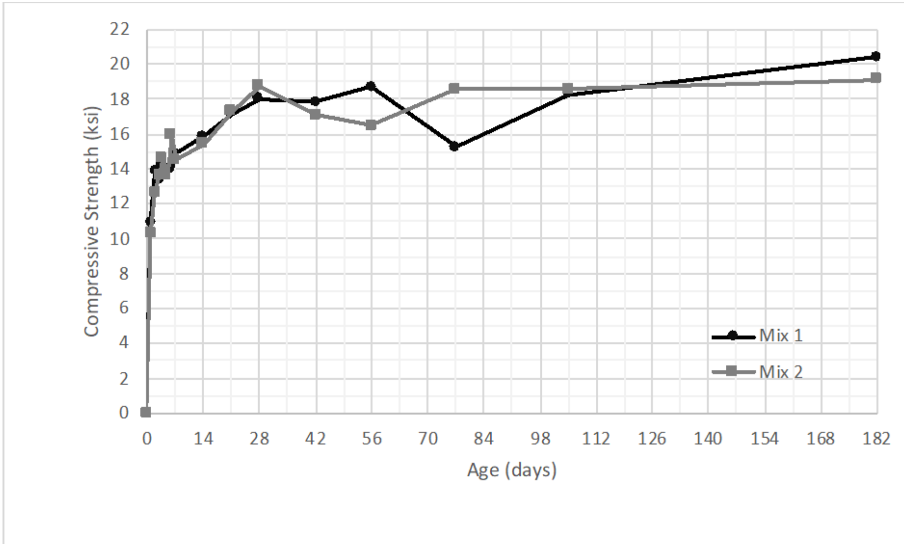


Figure 10: Strength Gain vs Time – 6 Months

4.3 Batch Size

The effect of batch size on UHPC performance was studied in this research by increasing the batch size from 2.5 to 4 cu. ft, and recording the flow, and compressive strength at 7, 28, and 56 days. The results from this study are presented in Table 7 and Figure 11. As can be observed, the batch size did not have a significant effect on the performance of the UHPC mix, with no clear trends in flow or compressive strength. The measured flows were all between 7.5 and 9.5 inches with a coefficient of variation of 8.6%. The measured compressive strengths had coefficients of variation of less than 6% on each day, with a coefficient of variation of only 3.2% at 56 days.

Table 7: Effect of Mix Size on Compressive Strength

Mix Size (cu. ft.)	Flow (in.)	Compressive Strength, f'c (ksi)		
		7-day	28-day	56-day
2.5	9	14.90	18.01	18.71
3	9.5	17.29	18.81	18.01
3.5	7.5	16.25	15.97	19.57
4	8.5	15.38	17.73	18.24
Average	8.63	15.95	17.63	18.63
C.O.V.	8.6%	5.7%	5.9%	3.2%

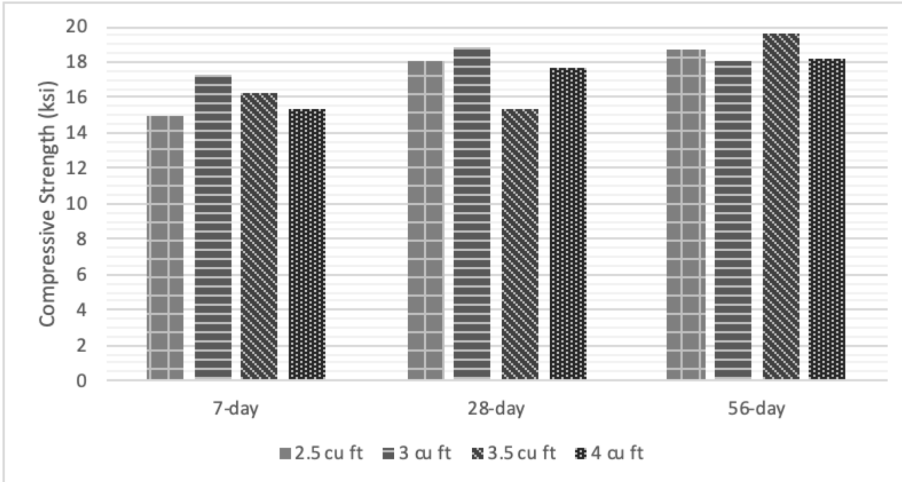


Figure 11: Effect of Mix Size on Compressive Strength

4.4 Temperature Effects

The effect of temperature on the performance of the UHPC mix was studied by varying the temperature of the dry UHPC constituents and by mixing the concrete at various outside temperatures. A total of 3 mixes were prepared and tested: a cold mix, a room-temperature mix, and a hot mix. The dry materials used in the cold mix were prepared by placing the materials in the structures cold lab at $32°F$ for 72 hours until the material came to thermal equilibrium. The batching and mixing were then performed outside when the temperature was $45°F$. This mix was performed early in the morning prior to the site being exposed to the sun, and the mixer was exposed to these conditions 2 hours prior to mixing. Similarly, for the hot mix, the dry constituents were prepared by placing them in the concrete lab oven at $90°F$ for 72 hours, and the mixing and batching took place outside in the sun when the temperature was $75°F$. It should also be noted that the mixer was outside and exposed to this environment for 2 hours prior to mixing. The temperature of the constituents used in the room-temperature mix were not altered from their lab condition ($60°F$), and the batching and mixing took place at the lab temperature ($70°F$).

The effects of temperature on the performance of the UHPC mix are provided in Table 8 and Figure 12. As can be observed, temperature had a noticeable effect on several performance measures. Specifically, flows decreased as temperature increased. That is, the cold mix had a flow of 10 inches, whereas the hot mix only had a flow of 6.25 inches. Similarly, the 7-day strengths decreased slightly with increasing temperatures. However, that same trend is not observable in the 28- and 56-day strength data. That being said, the hot mix had the lowest strength on all days, and although the set time was not directly measured, it was observed that the hot mix set significantly faster than the two lower temperature mixes. These results indicate that care should be given in mixing and placing UHPC at higher temperatures.

Table 8: Effect of Mix Temperature on Compressive Strength

Mix	Outside Temperature (°F)	Dry Material Temperature (°F)	Flow (in.)	Compressive Strength, f'c (ksi)		
				7-day	28-day	56-day
Cold Mix	45	32	10	16.15	17.89	17.98
Room Temperature	70	60	9	14.9	18.01	18.71
Hot Mix	75	90	6.25	14.78	16.62	17.03
		Average:	8.42	15.27	17.51	17.91
		C.O.V.:	18.8%	4.1%	3.6%	3.8%

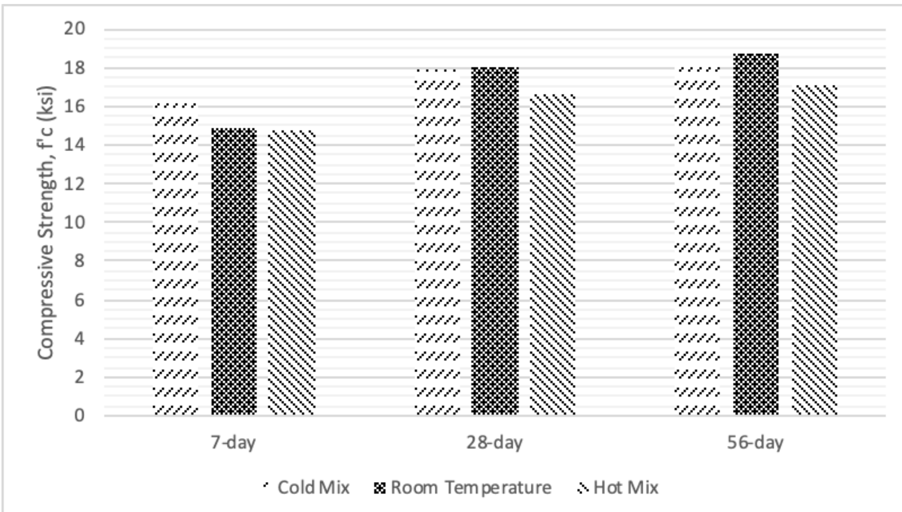


Figure 12: Effect of Mix Temperature on Compressive Strength

5 Summary

In this task, parameters that may affect field batching and mixing of UHPC were studied. Specifically, the rate at which UHPC gains strength over time was investigated, along with the effects that batch size and temperature might have on UHPC performance. It was observed that the UHPC mixes obtained high early strengths, exceeding 10 ksi in the first 24 hours. The mixes continued to gain strength over the duration of testing, ultimately reaching strengths of around 20 ksi at 182 days. Batch size was not observed to have a significant effect on flow or compressive strength; however, it was observed that the larger scale mixes used in this phase of research required 10% more water and HRWR in order to obtain the same performance observed for the smaller batches used in the material sensitivity study. Temperature was observed to have an effect on several parameters. Specifically, flow was observed to decrease with increasing temperature and the compressive strengths for the hot mix were consistently the lowest. These results indicate that care should be given while batching and mixing UHPC mixes at higher temperatures.

It should also be noted, that despite the wide range of mixing conditions studied in this phase of research, all mixes had flows of at least 6 inches, and respective 7- and 28- day compressive strengths of at least 13 and 16 ksi.

6 References

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